ISTEM - Strongly Incoherent Imaging for Ultra-High Resolution TEM

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The ISTEM (Imaging STEM) method [Phys. Rev Lett. **113**, 096101(2014)] constitutes a way for the realisation of TEM imaging with spatially incoherent illumination. Such incoherent image formation allows for an increased resolution and higher robustness towards chromatic aberrations compared to coherent illumination as used in conventional TEM (CTEM). This has been realised in scanning TEM (STEM) via reciprocity, which however suffers from other resolution-limiting factors such as scan noise or the finite extent of the electron source.

The ISTEM mode circumvents these problems entirely. It combines STEM illumination with CTEM imaging. A camera is used to acquire images formed by the focused electron probe that is scanning over the specimen while the imaging system is in imaging mode. With an exposure time chosen equal to the STEM frame time, the resulting image corresponds to a sum over the images of all probe positions. Because different specimen positions are illuminated at different times, the corresponding intensities are summed up incoherently. Beyond this simple explanation, the equivalence of the ISTEM illumination and CTEM with an extended and incoherent electron source can be furthermore rigorously shown mathematically within the mutual intensity formalism. From this, the gain of resolution can be intuitively understood in the limit of total incoherence, in which case the transfer is given by the autocorrelation of the coherent transfer function. The theoretical considerations also show that neither scan noise nor source size have any influence on ISTEM-images. Aberrations and defocus of the condenser system cancel out completely as well.

These predictions are confirmed by experimental ISTEM-micrographs of GaN in [11-20] and [1-100] projection which are found in good agreement with simulations. For the [1-100] direction neighbouring gallium and nitrogen columns at a distance of only 63 pm are resolved despite an information limit of 83 pm of the image-corrected microscope used for the acquisition. The classical information limit is thereby clearly overcome by 24%.

A relatively simple yet accurate analytical model for the image formation in ISTEM based on an object function approximation allows for the division of STEM intensity into a constant, a linear and a nonlinear term [Ultramicroscopy. **181**, 107(2017)]. Under certain conditions the formation of both linear and nonlinear terms can be expressed by convolutions with point spread functions. The findings of the proposed model are confirmed by comparison to multislice simulations. A close investigation of the linear coherent contrast transfer function allows the derivation of optimal imaging conditions to reach a maximum resolution for a given signal-to-noise ratio.

With the help of the principle of reciprocity, ISTEM can be made equivalent to any STEM mode by appropriate choice of objective and condenser aperture. This allows for the realisation of scan noise free annular bright-field STEM.

It can also be demonstrated, that the use of ISTEM for energy-filtered images suppresses the unwanted preservation of elastic contrast [Ultramicroscopy. **181**, 173(2017)].